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Processing of Metal and Oxygen From Lunar Deposits

Constance F. Acton

Metallurgical Processing

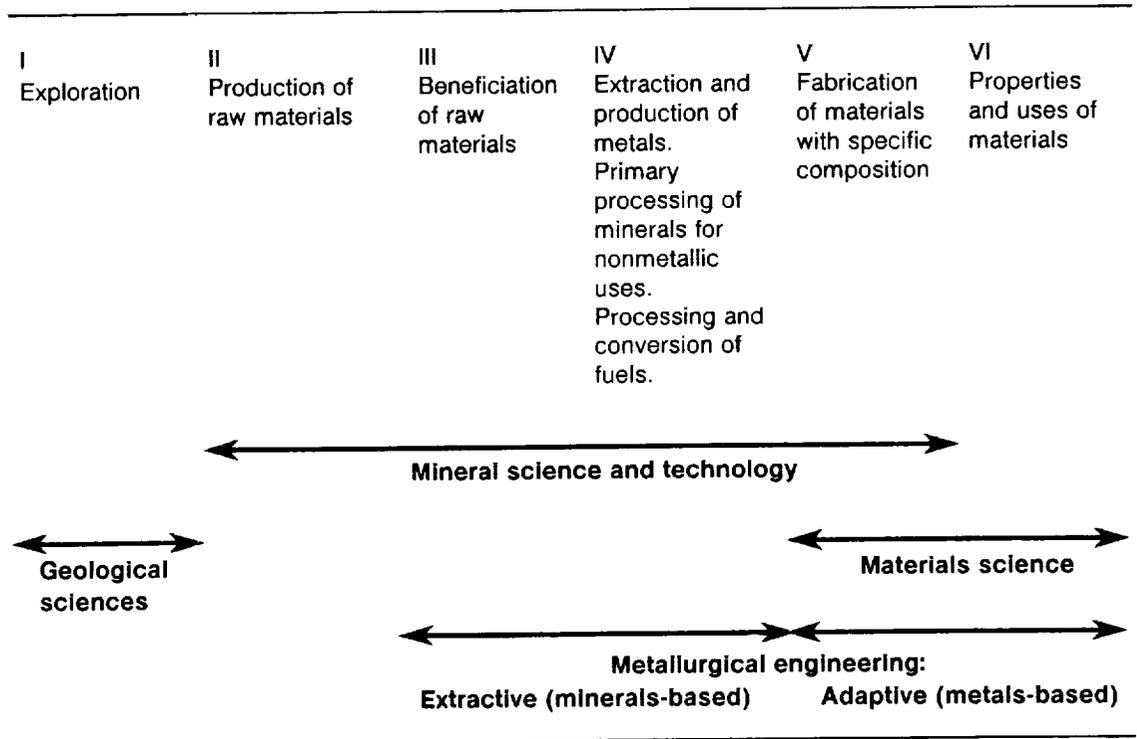
Introduction

Metallurgy—the art and science of economically concentrating, extracting, refining, and fabricating metals and alloys—has existed on Earth from antiquity. Gold, silver, and copper—elements that can occur as metals in their natural state—were used as long as

10 000 years ago. Metals extraction technology can be traced back at least 6000 years. Recently, major advances have been made in metallurgical processing. This developed field may now be ready for application to the production of metals in space.

Table 11 shows the steps involved in the production of mineral-based materials for commerce.

TABLE 11. *Steps in the Production of Mineral-Based Materials for Commerce*
[From Dresher 1974]



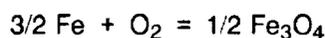
The first step is exploration to define potential sources of raw materials. The Apollo Program has defined some lunar resources; further exploration will undoubtedly find additional ones. Whether or not a metal-bearing deposit is classified as an ore, a reserve, or a resource is a question of economics. An ore is a resource that can be extracted at a profit. A reserve is a resource currently uneconomical to mine or greater than existing demand. A resource becomes a reserve or an ore if the proper technologies and economic conditions are developed.

The concentration of most metals in the crust of the Earth (or the Moon) is extremely low. And even the most abundant elements on Earth—iron, aluminum, silicon—cannot generally be extracted from common rock at a profit. A metal must be sufficiently concentrated in a mineral before it is mined.

Then the useful constituents of an ore must be separated from the residue (gangue) by the process of beneficiation. In this process, the ore minerals are concentrated by physical separation, exploiting differences in such properties as particle size, shape, and size distribution; specific gravity; magnetism; and electrostatics.

The importance of the beneficiation step cannot be overemphasized. Only after the ore minerals have been concentrated can economical metal extraction take place. On the Moon, some whole rocks may be ores for abundant elements, such as oxygen, but beneficiation will be important if metallic elements are sought from raw lunar dirt.

In the extraction process, a beneficiated metallic ore, such as an oxide, sulfide, carbonate, or silicate mineral, is converted to the reduced metal. Such minerals are the stable forms of metals in the Earth's or the Moon's environment. In the case of the important iron ore mineral magnetite (Fe_3O_4), the free energy of formation at 0°C is more than 120 kcal/mole O_2 according to the reaction



This explains the natural tendency of metallic iron to rust in air; that is, to convert to its thermodynamically stable oxide form. A very useful pictorial representation of the relative stability of metal oxides is an Ellingham diagram (fig. 33). These diagrams are also available for chlorides, fluorides, and sulfides.

Figure 33

Ellingham Diagram

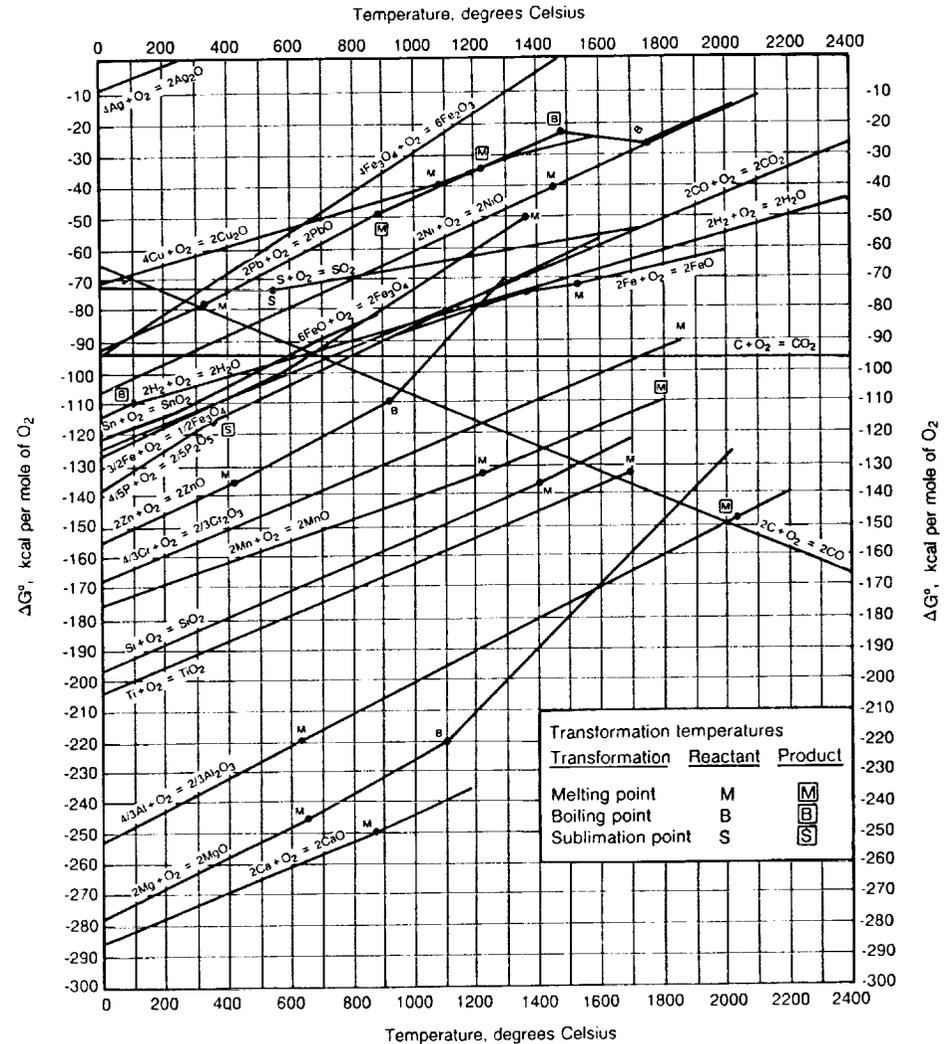
This diagram shows the standard free energy of formation of a number of oxides as a function of temperature. Accuracy varies between ± 1 and ± 10 kcal.

At 25°C the oxides produced by these reactions form with these free energies:

- | | | |
|------|---|-------------------------------------|
| (1) | $4\text{Ag} + \text{O}_2 = 2\text{Ag}_2\text{O}$ | -5.18 kcal per mole of O_2 |
| (2) | $2\text{C} + \text{O}_2 = 2\text{CO}$ | -65.62 |
| (3) | $4\text{Cu} + \text{O}_2 = 2\text{Cu}_2\text{O}$ | -69.96 |
| (4) | $\text{S} + \text{O}_2 = \text{SO}_2$ | -71.79 |
| (5) | $2\text{Pb} + \text{O}_2 = 2\text{PbO}$ | -90.5 |
| (6) | $4\text{Fe}_3\text{O}_4 + \text{O}_2 = 6\text{Fe}_2\text{O}_3$ | -93 |
| (7) | $\text{C} + \text{O}_2 = \text{CO}_2$ | -94.26 |
| (8) | $2\text{Ni} + \text{O}_2 = 2\text{NiO}$ | -103.4 |
| (9) | $2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O}$ | -116.42 |
| (10) | $2\text{Fe} + \text{O}_2 = 2\text{FeO}$ | -116.8 |
| (11) | $3/2\text{Fe} + \text{O}_2 = 1/2\text{Fe}_3\text{O}_4$
($3\text{Fe} + 2\text{O}_2 = \text{Fe}_3\text{O}_4$) | -121.2 |
| (12) | $2\text{CO} + \text{O}_2 = 2\text{CO}_2$ | -122.9 |
| (13) | $\text{Sn} + \text{O}_2 = \text{SnO}_2$ | -124.2 |
| (14) | $6\text{FeO} + \text{O}_2 = 2\text{Fe}_3\text{O}_4$ | -134.4 |
| (15) | $4/5\text{P} + \text{O}_2 = 2/5\text{P}_2\text{O}_5$
($4\text{P} + 5\text{O}_2 = 2\text{P}_2\text{O}_5$) | -146.1 |
| (16) | $2\text{Zn} + \text{O}_2 = 2\text{ZnO}$ | -152.1 |
| (17) | $4/3\text{Cr} + \text{O}_2 = 2/3\text{Cr}_2\text{O}_3$
($4\text{Cr} + 3\text{O}_2 = 2\text{Cr}_2\text{O}_3$) | -166.8 |
| (18) | $2\text{Mn} + \text{O}_2 = 2\text{MnO}$ | -173.6 |
| (19) | $\text{Si} + \text{O}_2 = \text{SiO}_2$ | -192.4 |
| (20) | $\text{Ti} + \text{O}_2 = \text{TiO}_2$ | -203.8 |
| (21) | $4/3\text{Al} + \text{O}_2 = 2/3\text{Al}_2\text{O}_3$
($4\text{Al} + 3\text{O}_2 = 2\text{Al}_2\text{O}_3$) | -251.18 |
| (22) | $2\text{Mg} + \text{O}_2 = 2\text{MgO}$ | -272.26 |
| (23) | $2\text{Ca} + \text{O}_2 = 2\text{CaO}$ | -288.8 |

The more energy is given off during the formation of an oxide, the more likely that oxide is to form and the more stable that oxide is. By the same token, the more negative the free energy of formation of an oxide, the harder it is to break that oxide down into the elemental metal and oxygen. Thus, the metals on the lower lines of this chart can reduce the metallic oxides on higher lines.

After Richardson and Jeffes 1948.



The larger the negative free energy of formation, the more stable the oxide. It can readily be seen that at 0°C the relative stability for oxides increases from iron through silicon and titanium to aluminum. The metals in the more stable oxides (lower on the chart) can chemically reduce the metals in the less stable oxides (higher on the chart). Also shown are lines for carbon and hydrogen, common reductants used in terrestrial extractive metallurgy. The challenge is to find procedures to extract the element of interest economically.

In some terrestrial cases, metals may be economically extracted at a higher than normal rate of energy consumption per unit of metal produced because cheap electrical energy is available; for instance, siting an aluminum smelter near a hydroelectric supply. In such a case, the rate of energy consumption may be 10-50 percent more than the general industry practice. The economics of utilizing metals from resources in

space are driven by transportation costs rather than energy costs. Many processes proposed for extraction of lunar materials are energy-intensive. Thus, the cost of energy on the Moon will be an important factor in developing processing technology. For example, concentrated solar heat will be cheaper than electricity and should be utilized where possible.

Geochemical Availability

Skinner (1976) has provided a lucid analysis of the geochemical availability of various elements on Earth. The basic concepts are directly applicable to the Moon. The most abundant metals in the Earth's crust are silicon, aluminum, iron, calcium, magnesium, sodium, potassium, and titanium (see table 12). For comparison, the composition of a typical lunar mare basalt [sample 10017, as analyzed by Wänke et al. (1970)] is also shown. To a first approximation, the compositions of terrestrial and lunar rocks are not too different.

TABLE 12. *Major Chemical Elements in the Earth's Crust and in a Typical Lunar Mare Basalt*

Element	Continental crust, weight %	Lunar sample 10017, weight %
Oxygen	45.20	40.7
Silicon	27.20	19.6
Aluminum	8.00	4.4
Iron	5.80	14.6
Calcium	5.06	8.2
Magnesium	2.77	4.8
Sodium	2.32	0.347
Potassium	1.68	0.206
Titanium	0.86	7.0
Hydrogen	0.14	---
Manganese	0.10	0.148
Phosphorus	0.10	---
Total	99.23	100.001

The geochemically scarce metals are those which do not normally form separate minerals but are present as substitutional atoms in common rock; for instance, lead or zinc may occur at ppm levels in orthoclase (KAlSi_3O_8). To release lead from the silicate structure, the entire mineral has to be chemically broken down, an extremely complex and energy-intensive process. "The mineralogical barrier" described by Skinner (see fig. 34) refers to the point at which

the easily processed minerals, such as sulfides, are so rare that mineral beneficiation techniques cannot be applied economically. At this level, the increased energy required to extract trace metals from silicates must be expended. Although the diagram is conceptual, the energy jump for the mineralogical barrier is 2 to 3 orders of magnitude higher than the energy required for the processing of typical ore minerals on Earth.

On Earth, mainly by means of free water, nature has concentrated the rarer metals in ore deposits. Such deposits are unknown on the dry Moon. On the Moon, metallic iron can be concentrated from soils, and iron and titanium oxides (ilmenite) and iron sulfides (troilite) can be concentrated from

soils or disaggregated rocks. Essentially all other known lunar ores are above the mineralogical barrier and will require considerable energy for their extraction. Examples include silicon and aluminum from anorthite and iron or magnesium from pyroxene.

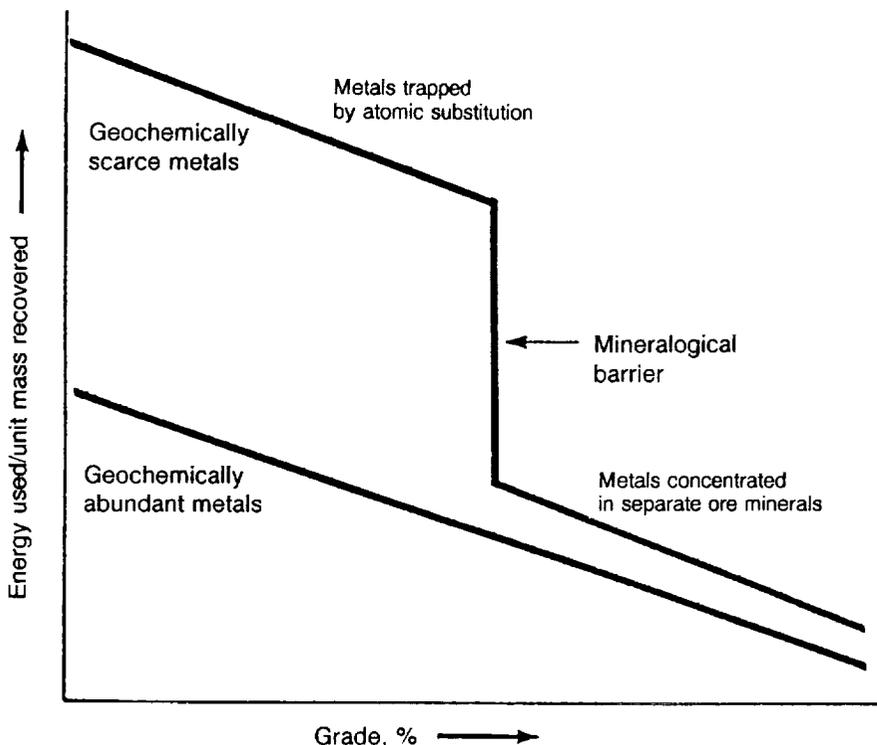


Figure 34

The Mineralogical Barrier

The relationship between the grade of an ore and the energy input per unit mass of metal recovered is shown for both scarce and abundant metals. A steadily rising amount of energy will be needed to produce even geochemically abundant metals from the leaner ores of the future, but the amount of energy needed to produce scarce metals will take a tremendous jump when the mineralogical barrier is reached. At that point, when ore deposits are worked out, mineral concentrating processes can no longer be applied, and the silicate minerals in common rocks must be broken down chemically to separate the atoms of scarce metals from all the other atoms. From Skinner 1976.

Extraction Technology

Extraction of various metals from mineral ores has developed into three subdisciplines: pyrometallurgy, electrometallurgy, and hydrometallurgy. In each subdiscipline, a different mechanism provides the driving force to reduce the combined metal to its elemental form.

In pyrometallurgy the force that drives the chemical reduction of a

metal oxide is high temperature. For many of the less stable metal oxides, carbon reduction at elevated temperatures is possible. This technology has been used successfully for iron smelting. (See figure 35.) For the more stable metal oxides, such as TiO_2 and Al_2O_3 , carbon reduction proceeds spontaneously (that is, the free energy becomes negative) only above $1630^\circ C$ and $2000^\circ C$, respectively. The disadvantages of high temperature extraction include

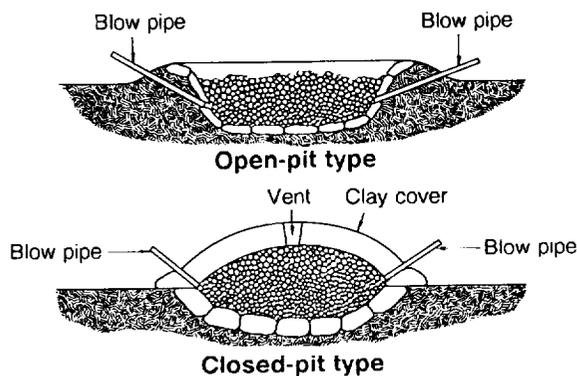
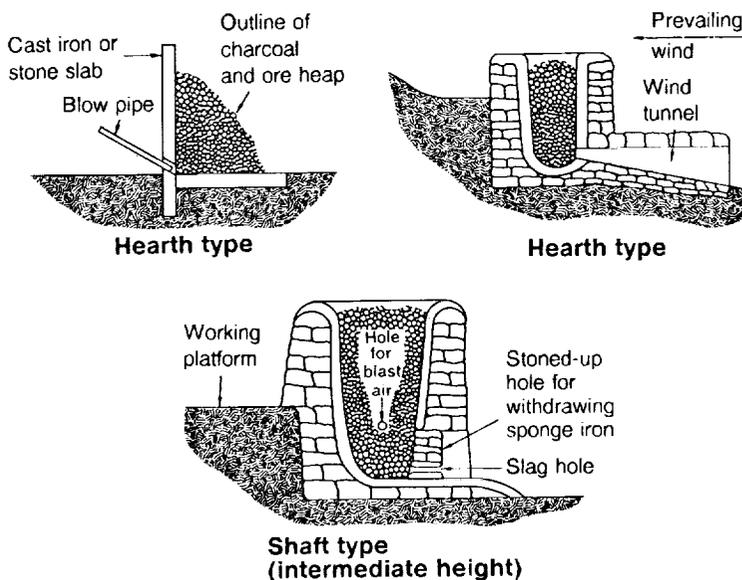


Figure 35

Iron Smelting

Iron smelting was discovered by ancient humans, changing the course of civilization. The basic process is one in which carbon (charcoal) is mixed intimately with iron oxide. Burning of the carbon produces carbon monoxide, which reacts with the iron oxide to produce metal and carbon dioxide, which is vented from the smelter. Many configurations were used in early smelters to optimize the delivery of oxygen and remove the metal and slag (residue) from the process. The slag consists primarily of impurities in the oxide ore.

Courtesy of the Association of Iron and Steel Engineers, reprinted from *The Making, Shaping and Treating of Steel*, 10th ed., fig. 1-2.



the large amount of energy required for heating, the difficulty in finding suitable container materials, and the problem of reoxidation of the molten metal.

In electrometallurgy an electrical rather than a chemical driving force is used to reduce the metal oxide. An example of a well-developed electrometallurgical technology is the extraction of aluminum from Al_2O_3 by

electrolysis in molten fluoride salts.

Hydrometallurgy exploits the fact that certain minerals are soluble in aqueous solutions such as sulfuric acid. Once dissolved, the metal ions can be recovered by low-temperature electrolysis, precipitation, chemical reduction, ion exchange, or solvent extraction. (See figure 36.)

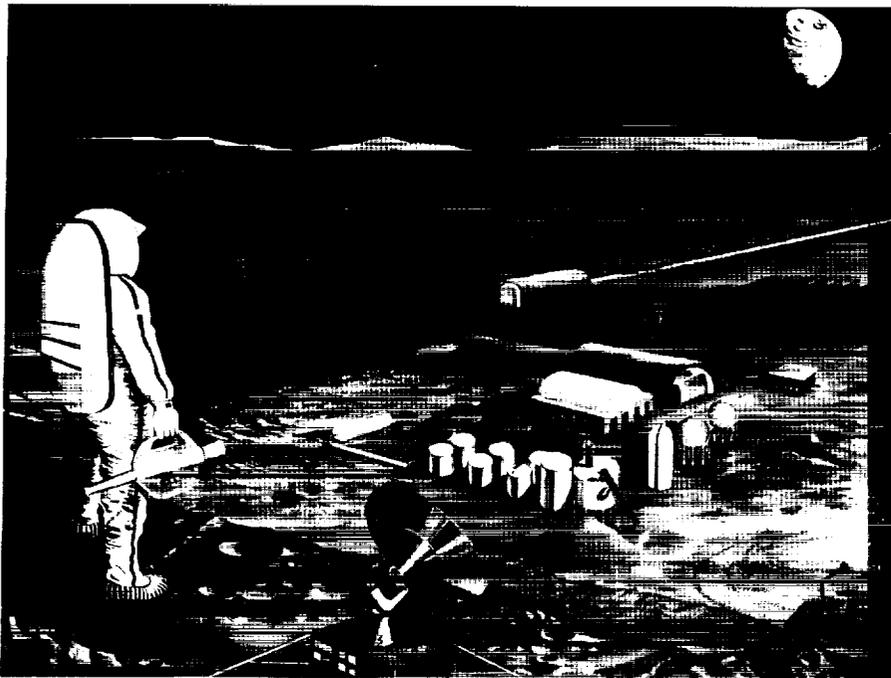


Figure 36

Chemical Extraction Plant on the Moon

In this artist's concept of a lunar chemical plant, metals and oxygen are extracted from lunar soil using relatively low-temperature aqueous chemistry. First, lunar soil and crushed rock are leached in aqueous hydrofluoric acid (HF) in the tank with the chute and chimney, making metal fluorides. The metal fluorides in solution are further processed in the tall and short cylinders and then electrolyzed in the light-colored building with the pillars, producing oxygen and metals at the electrodes.

Oxygen is liquefied and stored in the spherical tanks (two large ones and many small ones under a roof). The HF is recovered, recycled, and stored in the vertical cylinder on the right. The horizontal cylinder on the left holds the water needed for this aqueous process.

The upright panels in the background to the right radiate the excess heat generated by the process. The flat solar panels in the background to the left supply power to the electromagnetic launcher in the middle background, which will shoot lunar products to orbit. The soil-covered buildings in the middle provide workshops and housing for the lunar pioneers.

Artist: Scott Berry

Courtesy of William N. Agosto, Lunar Industries, Inc.

The scarcity of water and the abundance of solar energy available at nonterrestrial sites suggest that pyrometallurgy or electrometallurgy will be favored as processing technologies there. Processes that conserve volatile substances by recycling will be essential to minimize the transport of makeup chemicals, as will be processes that limit the consumption of special materials, such as fluxes or anodic substances, which would have to be transported to space.

This discussion of geochemical availability and extractive metallurgy implies that extraction of minor elements in space is questionable unless specific natural concentrations are discovered or energy becomes very inexpensive. The relative costs of scarce and abundant metals will become even more disparate in the future on Earth as well as in space. It may be more cost-effective to substitute the lesser properties of an abundant metal like iron or aluminum than to attempt to extract a geochemically scarce metal. This line of thought suggests that effort be directed to extracting iron on the Moon rather than to recovering scarcer metals (such as those from the platinum group) from asteroids. When exploration and timing difficulties are added to the energy consumption considerations, the

case for going after the rarer precious metals becomes yet weaker.

Proposed Extraction Schemes

Introduction

In the following section, a variety of plausible processing technologies are described. In general it may be said that these technologies are derived from a limited amount of terrestrial experience and are totally untested in application to the extraction of nonterrestrial resources. Work must be initiated in the near future to sort out these and other proposals, for it is the experience of the metallurgical industry that such processes require much development and testing, at bench-top and pilot-plant levels, before production facilities are achieved. Development times of 10 to 25 years have been experienced, and many false steps have been taken. For example, an Alcoa plant for extraction of aluminum metal from anorthite by carbochlorination and electrolysis of aluminum chloride was constructed at a cost of \$25 million, only to be shut down after a short operating time because of technical problems.

Many process schemes have been proposed for recovering a variety of metal products and volatiles from a variety of lunar feedstocks. A collection of pyrometallurgical, electrometallurgical, and hydrometallurgical approaches have been proposed, with varying amounts of research and engineering data to support them.

The participants in this study looked at scenarios for the development of space resources in the next 25 years. The materials subgroup of study participants reached the consensus that, within this timeframe, oxygen production from lunar resources will be the major objective of the space program. The participants also assessed what metals recovery technologies can be implemented and suggested what time would be required to develop more complex metal processing technologies.

Recovery of Meteoritic Iron

History and thermodynamics teach us that the most appropriate metal to recover first is iron. The most basic approach to recovering iron on the Moon is to process the meteoritic iron found in lunar soils. Small chunks of meteoritic iron have been found in lunar samples, but most metal exists in the form of micron-size particles, particles encapsulated by or attached to silicates or glasses.

The first processing effort should be to concentrate this elemental iron by mineral beneficiation techniques (such as magnetic separation). Current knowledge does not suggest that regions of elevated metal content can be found, but additional information on the abundance and ease of separation of the metal is needed. In addition, trace elements in the iron must be identified. Alloying elements or solutes can have a profound effect on the iron's mechanical properties. The iron and steel industry has probably never looked at iron alloys of lunar composition, because carbon and other solutes are always introduced in the smelting process.

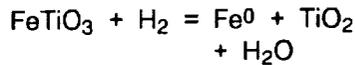
The utilization of meteoritic iron is suggested as a first approach because it does not require the energy-intensive and chemically complex step of extraction. However, a process for separating the metal from adhering silicate minerals must be developed. The recovered lunar iron can either be processed directly into parts by powder metallurgical techniques or be melted at about 1550°C and cast into ingots for wrought products.

Even though this is the simplest process for producing lunar iron and the technologies for beneficiation, melting, and pressing or casting and forming are fairly

well developed on Earth, the application of these technologies in the lunar environment will present many challenges.

Processing of Lunar Ilmenite

The next simplest process for recovering iron is to reduce it from ilmenite (FeTiO_3). For the reaction



the free energy at 1000°C is 5.86 kcal/mole. This gives a very low equilibrium constant $K_c = 0.103$ at 1000°C . Thus, the reduction of ilmenite to reduced iron plus TiO_2 is not strongly favored thermodynamically and may not proceed to completion. Furthermore, the reaction will not proceed to the right unless H_2O (g) is removed from the system. Thus, if thermodynamically favorable, the rate of reaction must be determined.

Another ilmenite reduction scheme based on a commercial process has been suggested for the Moon (Rao et al. 1979). In it the ilmenite is reacted with carbon to reduce FeO to Fe^0 . The iron from the ilmenite is chlorinated at 800°C in a fluidized bed reactor while the TiO_2 remains unchanged.

The FeCl_3 gas is condensed and could be reacted with oxygen gas at $300\text{-}350^\circ\text{C}$ in a second fluidized bed to produce Fe_2O_3 . The Fe_2O_3 could then be reduced with either carbon or hydrogen gas below 1000°C to produce low-carbon steel or iron. The CO or H_2O formed would be recycled to recover the oxygen. Alternatively, the FeCl_3 could be reduced directly to metallic iron with hydrogen at 700°C . The hydrogen chloride formed as a byproduct would be recycled. The flow diagram for this conceptual process is shown in figure 37.

The residue in this process is TiO_2 , which can be further processed to recover titanium metal. Since titanium forms a highly stable oxide, it cannot be reduced with carbon or hydrogen. It can, however, be reduced with calcium metal. A process has been developed to perform this reduction by pelletizing TiO_2 and calcium metal powders and heating at $925\text{-}950^\circ\text{C}$ for several hours. The CaO is then preferentially dissolved by acid leaching. Disadvantages here are that the acid and water must be recycled and that water is not available at the site. Calcium metal could be provided from processing of anorthite for aluminum.

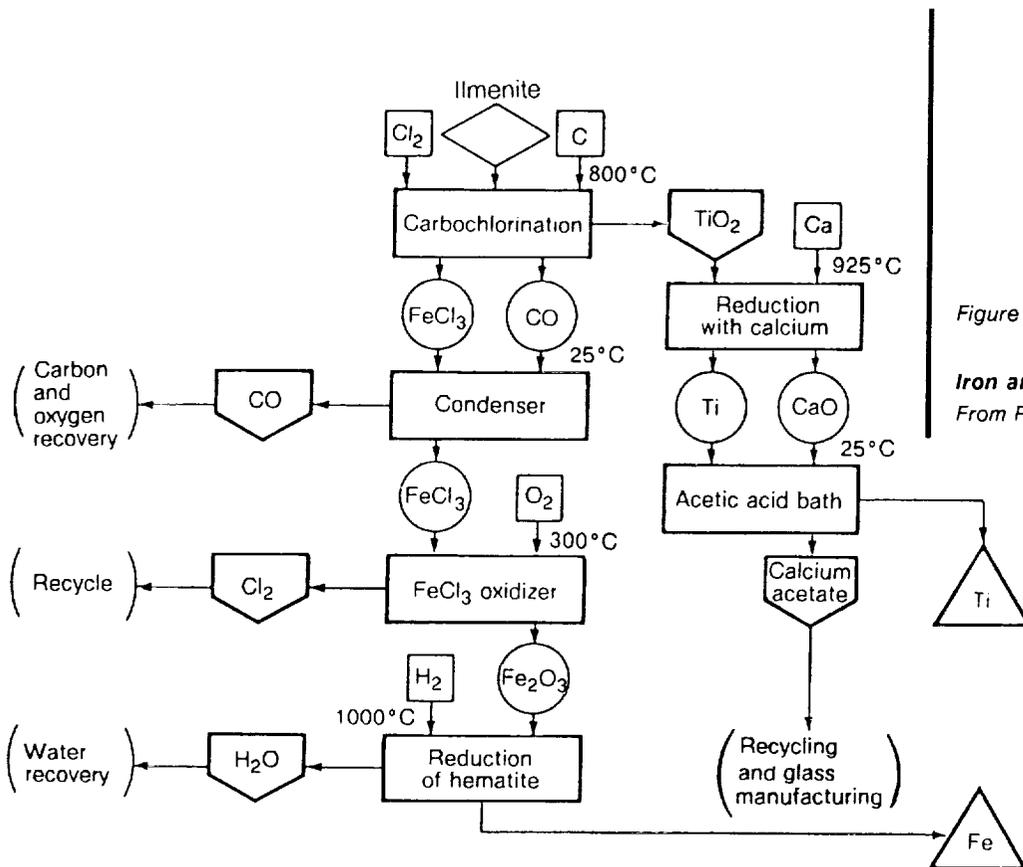


Figure 37

Iron and Titanium Processing
From Rao et al. 1979.

The most likely end product of ilmenite processing is a partially reduced mixture of Fe, FeO, TiO₂, and other impurities. There are several possible options for using this type of product.

The simplest is not to try to recover the iron but rather to use the material as is to form "cermet" blocks for construction. Assuming that 50- to 200- μ m particles are produced from the fluidized bed reactor, sintering may be successful at temperatures just below the melting point of iron. To evaluate this option further, considerable test work on pressing (using, for example, a hot isostatic press) should be done on simulated residues. If this option proves unsuccessful, the iron-titania residue may simply be stockpiled until such time as more advanced processing technology is developed for the lunar site.

If iron recovery is required and the chlorination process does not prove feasible, simply melting the iron out of the residue may successfully produce a crude iron alloy suitable for structural uses. Alternatively, a low-temperature carbonyl process could be utilized to extract the iron.

Other Proposed Processes

For lunar processes to be successfully developed, certain guidelines must be kept in mind.

These include the following:

- Pyrometallurgical and electrometallurgical operations are favored. Because of the lack of available water on the Moon, hydrometallurgical operations will require additional development to recover process water with high efficiency.
- Reductants such as chlorine, hydrogen, and carbon, if not obtainable from lunar sources, must be brought from Earth and therefore should be recycled to minimize their resupply.
- The processes should be tailored for the high-vacuum, low-gravity space environment. Alternatively, methods for providing inexpensive pressurized volumes would have to be developed.
- The oxygen produced in the metal recovery process will be more important than the metal recovered, at least in the early phases.

The NASA SP-428 paper (Rao et al. 1979) was written by recognized metallurgical experts who did a competent job of assessing the available thermodynamic and kinetic literature for several aluminum, titanium, iron, magnesium, and

oxygen extraction processes. Their analysis of the research done and needed may stand up to scientific scrutiny by their peers. None of their candidate processes, however, has been sufficiently tested to provide the data needed for process plant design by a competent engineering company.

A number of other processes have been referred to at this workshop. These include acid leaching, alkali leaching, fluorination, electrolysis, basalt vaporization, plasma smelting, and sulfide processing. Some of these processes can be summarily dismissed for such reasons as requiring large amounts of water or of a nonlunar reductant, impracticality of recycling, or requiring extraordinary amounts of energy. For those few which may warrant less cursory evaluation, the basic scientific data have not yet been provided.

Process Development

What is needed *at a minimum* to establish credibility in the scientific community is compelling thermodynamic and kinetic data for any proposed system.

Before any research work can begin, it is obvious that a comprehensive literature review must be done. Any pertinent

thermodynamic data must be critically evaluated. The feed material must be realistically characterized in terms of physical and chemical properties. The stoichiometry and phase relations for the system must be known.

The thermodynamic properties of the system should be determined experimentally. The extent of deviation from calculated thermodynamic values for condensed and vapor phases should be measured. Appropriate phase diagrams should be constructed relating phase composition, free energy of formation, and temperature; e.g., phase diagrams for the elements in the ilmenite (Fe-Ti-O) and for the products of the ilmenite reduction process (Fe-Ti-O₂-H₂) for temperatures between 700 and 1000°C. The vapor phase and residue should be accurately analyzed as well.

If the thermodynamic data indicate an attractive extraction process, the kinetics and heat and mass transfer properties must next be systematically investigated.

It should be noted that experimental programs for high-temperature processes are extremely difficult and may require several years' effort.

Assuming that the proposed process has been demonstrated by such a bench-scale program to be feasible, it is appropriate before proceeding further to do an economic evaluation of the process. Operating and capital costs should be assessed, and special considerations, such as mass and energy requirements, need to be carefully analyzed.

If the process still appears attractive, then a terrestrial pilot plant is mandatory. If the process does not work on Earth, it probably cannot be made to work on the Moon. A great deal of consideration would have to go into designing a

pilot plant that would yield useful information regarding a plant at a nonterrestrial site. Even for the very simplest of processes, it is clear that its development for use on the Moon would require an intensive research and development program. If begun now, the most optimistic program for an ideal process would probably take 20-50 years and involve hundreds of millions of dollars.

Thus, if lunar resources are to be used in the early 21st century, there is a clear need to begin a research and development program now. It should proceed through the stages presented in table 13.

TABLE 13. *Research and Development Program for a Lunar Metal Recovery Process*

Stage	Time	Personnel	Cost	Comments
1. Technology review	6 months	Metallurgical specialists	Modest	
2. Experimental research	3-5 years	Researchers at several institutions concurrently	Considerable	Although iron, aluminum, silicon, and titanium should all be evaluated, priority should be given to iron, which is thermodynamically the least stable oxide and the metal with the largest body of known technology.
3. Pilot plant	2 years or more	R&D engineers	Significant	
4. Plant design	2-3 years	Engineering and construction team	Unknown until phases 2 and 3 are completed	All of the process technology developed would be translated into hardware amenable to lunar operation.
5. Hardware construction	3-5 years	Manufacturing and construction personnel	Unknown until phase 4 is completed	Hardware could be constructed on Earth or on the Moon or both.
6. Plant startup	1-2 years	Engineering and construction team	Unknown until phase 4 is completed	

A fair amount of speculation on metal recovery processes has been made, but so far little of the work can stand up to scientific scrutiny. To build a workable lunar materials recovery plant, the logical program described must be followed. Sufficient amounts of capital and work time by qualified metallurgical personnel must be provided.

Experts in the fields of mineral science and metallurgy must contribute to the development of the required new process technology. The most effective means of achieving this objective is by joint cooperative efforts between established metallurgical experts and specialists in the planetary sciences. If the space program attempts to develop metallurgical capabilities in-house, the timing objectives for the new technology will be impossible to meet.

Applicability of Space Technology to Terrestrial Metal Processing

Metallurgical technology on Earth has developed slowly with a limited base of trained technologists and R&D funding. The research is very difficult experimentally, complex, and hard to scale up. Hence, process development is slow.

It seems obvious that even a minor R&D effort by the space program would be a major contribution to the existing body of knowledge. Although it is impossible at this time to judge what metal processing technologies will be developed for space in the next 25 years, it is of interest to use some general guidelines to speculate, as follows.

Chloride and fluoride systems offer interesting potential for metal extraction. Such processing schemes would provide a technology base for a terrestrial metallurgical breakthrough that would reduce energy consumption per unit output. Along with the process chemistry, the development of recycling technology could clearly be advantageous in dealing on Earth with ever increasing environmental limitations.

Development of electrochemical, electrode, or electrolysis technologies for metal extraction, refining, or processing could advance the currently rather empirical state of the art on Earth for certain metals.

The development of a computer interface with metallurgical process technology would likely advance the state of metallurgy by several orders of magnitude and is

one of the most exciting prospects for change.

Metals produced by new technology on the Moon will not contain the solutes usually contained in their counterparts on Earth, such as carbon and sulfur in steel. Physical and mechanical properties of a whole new cadre of alloys will be measured. The creation of such uncontaminated alloys will advance the field of materials science since the effect of impurities on properties can be zeroed out. Such new alloys may be used on Earth for unique applications, now impossible to fulfill.

And new metallurgical technology developed to extract metals from alternate mineral feedstocks could have strategic and possibly commercial value on Earth.

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